

When less is more: Are radio galaxies below the Fanaroff-Riley break more polarized on parsec scales ?

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ABSTRACT

We present images showing the first detections of polarization on parsec scales in the nuclei of four Fanaroff-Riley type I (low-luminosity) radio galaxies. Observations with Very Long Baseline Interferometry at λ 3.6cm reveal the presence of ordered magnetic fields within ~ 1650 Schwarzschild radii of the putative central supermassive black hole. The relatively high fractional polarization in the pc-scale jets of these galaxies is consistent with the standard scheme unifying low-luminosity radio galaxies with BL Lac objects. This result also suggests that these radio galaxies lack the obscuring tori that apparently depolarize the nuclear emission in the more powerful FRII radio galaxies, and that their supermassive blackholes are poorly fed and/or inefficient radiators.

Subject headings: galaxies: active — galaxies: individual (3C 66B, 3C 78, 3C 264, 3C 270) — galaxies: magnetic fields

1. INTRODUCTION

Fanaroff & Riley (1974) were the first to point out that radio galaxies with 178 MHz luminosities below and above 2×10^{25} WHz⁻¹ display different kpc-scale radio morphologies: radio galaxies below this divide (FRI) have plume-like structures, while those above

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this divide (FRII) have well-collimated jets terminating in so-called hot spots. Based on comparisons of orientation-independent properties, it has been widely argued that FRI radio galaxies constitute the parent population of the strongly Doppler beamed BL Lac objects, while FRII radio galaxies, particularly those with narrow emission lines, constitute the parent population of radio-loud quasars (Urry & Padovani 1995, and refs. therein).

Magnetic (B) fields are believed to be instrumental in the formation and collimation of the synchrotron-emitting relativistic jets ejected by radio-loud active galaxies (Blandford & Payne 1982). Ordered pc-scale B -fields have been detected in active galaxies with highly Doppler beamed jets via polarization-sensitive Very Long Baseline Interferometry (VLBI) (Gabuzda et al. 1994, and refs. therein). However, direct evidence for such fields is meagre in galaxies whose jets are believed to be closer to the plane of the sky (and therefore not heavily relativistically beamed) (Taylor, Hough, & Venturi 2001; Middelberg 2004). In particular, there have been no detections of pc-scale polarization for any radio galaxy below the FR luminosity divide. In this letter we report the detection of appreciable polarization on parsec scales in the nuclei of four FRI radio galaxies. We discuss the significance of our results in the context of the FR divide and the standard radio-loud Unification Scheme.

2. OBSERVATIONS AND DATA REDUCTION

We observed the four FRI radio galaxies *viz.*, 3C 66B, 3C 78, 3C 264 and 3C 270, at 8.4 GHz (λ 3.6cm) with the Very Large Baseline Array (VLBA)⁴ and five stations of the European VLBI Network⁴ *viz.*, Effelsberg, Onsala, Yebes, Medicina, and the phased WSRT, on 2002 March 1. The observations were made in a “snap-shot” mode with the observing time per target totalling five to eight hours. The total data rate was 128 Mbits/sec, with 8 MHz recorded in each of the four baseband converters (BBCs) for each right- and left-circular polarization and with two-bit sampling. All antennas observed both right- and left-circular polarization, except for Onsala and Yebes, which observed only RCP. The data were correlated at the MkIV Data Processor at JIVE.

The calibration and imaging of the data were done using standard techniques in the AIPS package, using system temperatures and gain curves provided by the NRAO and EVN, and Los Alamos as the reference antenna. The unpolarized source 3C 84 was used to determine the instrumental polarizations (D-terms) of the antennas using the AIPS task

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LPCAL. The instrumental polarizations for the WSRT were very high ($\sim 20\%$); and it was not possible to adequately calibrate and remove these D-terms. We therefore flagged all the WSRT polarization data before running LPCAL, which led to refined values for the remaining D-terms. The compact, polarized source 1156+295 was used to calibrate the polarization position angles, by comparing the polarization in our VLBI map with the integrated 8.4 GHz polarization measured on 2002 March 8 from the NRAO VLA monitoring database⁵.

The AIPS tasks IMAGR and CALIB were used to make the total intensity (I) images. Since Onsala and Yebes recorded only RCP, the polarization $u - v$ coverage was not symmetric, so that the polarization (P) beam was complex. Accordingly, the AIPS procedure CXPOLN and task CXCLN were initially used to make the polarization maps. The resulting P images had appreciably higher noise levels than those obtained by excluding the polarization data for Onsala and Yebes, and we adopted the latter images as our final polarization images. We used a large empty region covering typically > 200 beam areas to estimate the rms noise of the I image and ~ 100 beam areas for the rms noise of the P image (Table 1).

The spatial resolution of the images is ~ 0.5 mas, corresponding to $\sim 0.2\text{--}0.4$ pc. Significant polarization was detected from the inner parsec, *i.e.*, the “cores” and/or inner jets of all four FRI radio galaxies. Figure 1 shows the total intensity images of the four FRIs with the polarization electric vectors and the distribution of the degree of polarization (in color) superimposed.

3. DISCUSSION

Pc-scale Polarization – B -field Geometry: Comparisons with VLBI maps with similar resolution obtained at other frequencies (e.g., Giovannini et al. 2001; Jones & Wehrle 1997) confirm that, in each case, the brightest radio component has a flat or inverted spectral index, and can be identified as the VLBI “core.” The fractional polarization in the pc-scale radio cores is $m_c \simeq 0.4 - 1\%$, with the degree of polarization rising to $m_{i-j} \simeq 5 - 10\%$ in the inner jet (≤ 1 pc from the core; see Table 1). We also detected jet polarization of $m_j \sim 20\%$ further from the cores of 3C 78 and 3C 264, and m_j reaches 60% in a knot about 1.5 pc from the core of 3C 264. These values are comparable to those observed for the pc-scale jets of BL Lacs and quasars, indicating the presence of appreciably ordered B -fields and little depolarization.

When the source is optically thin to the emitted synchrotron radiation (as is the case

⁵<http://www.vla.nrao.edu/astro/calib/polar>

for the jets), the observed polarization angle is orthogonal to the B -field in the emission region, while the polarization angle and source B -field are aligned when the emission region is optically thick (Pacholczyk 1970). In this case, the inferred jet B -fields within one parsec of the cores of 3C 66B and 3C 78 are roughly transverse to the local jet direction, while the relative B -field orientation in the inner jet of 3C 264 is unclear; it may be oblique to the flow direction, but no definite conclusion can be drawn because we cannot account for possible bends in the jet on scales smaller than our beam or for local variations in Faraday rotation. 3C 270 has no detected polarization beyond its core (Fig. 1).

BL Lac objects most often have transverse jet B -fields on parsec scales, originally taken as evidence for shocks that compress an initially disordered field (e.g., Gabuzda et al. 1994). However, Gabuzda, Murray & Cronin (2004) found that at least some of these jets have a transverse rotation-measure gradient, which is a signature of an ordered toroidal B -field component (Blandford 1993), possibly associated with a helical B -field. The development of an appreciable longitudinal B -field component with distance from the core has also been observed for a number of BL Lacs (e.g., Pushkarev et al. 2005, hereafter P05). The jet B -field geometries in 3C 66B and 3C 78 are both typical of those that are observed in BL Lac objects, providing support for the standard unification picture. If the transverse field in 3C 66B is associated with an ordered toroidal B -field component and not shock compression, this component begins to be the dominant ordered component on scales as small as ~ 0.3 pc from the core, assuming a black-hole mass of $1.9 \times 10^9 M_\odot$ (Noel-Storr et al. 2005, preprint) and an inclination $\theta \simeq 40^\circ$ (Giovannini et al. 2001). This corresponds to only ~ 1650 Schwarzschild radii from the putative central supermassive black hole.

Three of the four FRI radio galaxies show one-sided “core–jet” pc-scale structures as is characteristic of radio-loud active galaxies, believed to be due to Doppler boosting/dimming of the approaching/receding jet. The fourth, *viz.*, 3C 270, shows a two-sided jet, suggesting that it is inclined closer to the plane of the sky. It is noteworthy that the two radio galaxies with the highest jet-to-counterjet intensity ratios (*i.e.*, those expected to be most highly Doppler beamed of the four), *viz.*, 3C 78 and 3C 264, have more detected polarization and structure in their jets than the other two sources.

3C 78 shows a clear alternation of regions with transverse and longitudinal inferred B -field along its jet, reminiscent of similar alternating B -field structures observed in the BL Lacs OJ 287 (Gabuzda & Gómez 2001) and 1418+546 (P05), which have been interpreted as evidence for “global” intrinsic fields associated with the jets. We also observe a region of roughly longitudinal B -field shifted toward the southern edge of the jet of 3C 264 (~ 1.3 pc from the core). This could be a consequence of shearing of the jet due to its interaction with the surrounding medium (Laing et al. 1999), or alternatively may come about because the

jets have a helical B -field (Lyutikov, Pariev, & Gabuzda 2005). Such polarized “sheaths” have been observed in the quasar 1055+088 (Attridge, Roberts, & Wardle 1999; P05) and a number of BL Lacs (P05).

Pc-scale Polarization – FR Divide and Unification: In contrast to our detection of pc-scale polarization in the nuclear regions of all four of these FRI radio galaxies, such polarization was detected in only one of four narrow-line FRII radio galaxies (Taylor et al. 2001; Middelberg 2004; Zavala & Taylor 2002): weak polarization with $m_c \simeq 0.2\%$ was detected only in the flat-spectrum core of 3C 166. Even if results for broad-line FRII radio galaxies are included, the core-region polarization detection rate remains only about 25%: two of eight FRII radio galaxies, *viz.*, 3C 166 and 3C 111, show polarization in their 8 GHz pc-scale cores. In contrast, four of eight FRI radio galaxies show core-region polarization with $m_c \geq 0.4\%$. This detection rate increases to 100% if we exclude those galaxies that are in cooling flows (*viz.*, 3C 274, 3C 317, 3C 218) or recent mergers (NGC 5128), and are therefore expected to be lying in regions with high Faraday depths (Sarazin & Wise 1993) that may strongly depolarize the emission.

The comparatively low core polarization in the FRII radio galaxies may be due to depolarization by a foreground screen that is fragmented on scales smaller than the spatial resolution; candidates for such foreground screens include the inner ionized edge of an obscuring torus (Zavala & Taylor 2003), photoionized clouds in the broad-line and narrow-line regions (Zavala & Taylor 2002), ionized confining gas in the narrow-line region (Zavala & Taylor 2003) and an accretion disk corona around the central engine (Middelberg 2004). While several FRII galaxies show evidence for a torus (Urry & Padovani 1995), searches for obscuring tori in FRI galaxies have not yielded definitive results. NGC 5128 shows signs of a torus-like disk (Alexander et al. 1999), but recent infrared observations of 3C 274 by Perlman et al. (2001) failed to detect emission from a dusty torus. Studies of FRI galaxies on parsec scales have revealed neutral-hydrogen (HI) absorption in thin gaseous disks, with the cores being essentially unobscured (Taylor 1996; Morganti et al. 2002). Our detection of polarized emission from the core region of 3C 270, which also displays HI and free-free absorption in a nuclear gas disk, likewise suggests that the circumnuclear disk is thin (in agreement with the predictions of Jones & Wehrle (1997) and van Langevelde et al. (2000)), so that it fails to depolarize the emission from the mostly unobscured core.

It is interesting that the core fractional polarization of BL Lacs and quasars (the purported Doppler beamed counterparts of FRIs and FRIIs) differ, being $m_c \sim 2 - 5\%$ in BL Lac objects and $m_c < 2\%$ in quasars (Gabuzda et al. 1994; Pollack, Taylor, & Zavala 2003). The origin of this difference is not entirely clear, but space-VLBI polarization observations at 5 GHz have shown that the ground-based VLBI “core” polarization of BL Lac

objects are dominated by the contribution of newly emerging, highly polarized jet components (Gabuzda 1999; Gabuzda & Gómez 2001, P05). The modest core polarization in both the BL Lacs and quasars could be due to the weakness of the ordered B -field component or depolarization by circumnuclear thermal material. Zavala & Taylor (2003) derived smaller rotation measures in the pc-scale cores of several BL Lacs than is typical for quasars, and this trend is confirmed by results for a much larger sample of BL Lac objects (Gabuzda and Pashchenko, in prep.). This suggests that BL Lac objects have less ionized gas in their central regions, which could explain both their higher core polarization (lower depolarization) and their almost featureless optical spectra. This is also consistent with the possibility that FRI sources lack both an obscuring torus and substantial amounts of ionized gas, since this gas should be unobscured and should therefore give rise to lines in the optical spectrum; indeed, Baum, Zirbel, & O’Dea (1995) have demonstrated that the optical emission lines of FRI galaxies are systematically less luminous than those of FR II galaxies. Note also that the core polarization angles in 3C 66B and 3C 264 are both nearly transverse to the jet direction; although we cannot infer the corresponding B -field geometry without knowing whether the region of polarized emission is optically thin or thick, the small offset of the observed polarization angles from being strictly orthogonal to the jet suggests an absence of substantial Faraday rotation, consistent with a dearth of thermal free electrons in the core regions of these galaxies.

4. SUMMARY AND CONCLUSIONS

Our global VLBI polarimetry of the nuclei of four radio galaxies of the FRI type at λ 3.6cm and a typical angular resolution of 0.5 mas have yielded the following results:

1. We have obtained secure detections of polarization between 0.4–1% within a \sim parsec sized region in all the nuclei.
2. Although we are dealing with small numbers, this suggests that the detection rate of nuclear polarization for FRI radio galaxies is considerably higher than that for FR II galaxies.
3. If the lower degree of nuclear polarization in FR IIs is due to depolarization by the inner ionized edge of an obscuring torus, the higher detection rate in the FR Is would suggest that the latter lack such a torus or other ionized material around the bases of their nuclear jets.
4. The detected inner-jet polarization is oriented parallel to the local direction of the jets in 3C 66B and 3C 78, implying a transverse B -field in these jets, as is typical of BL Lac objects. In 3C 264 and 3C 270, the orientation of the polarization in the inner jet and core, respectively, relative to the local jet direction is unclear due to possible resolution and/or

Faraday rotation effects. We also find evidence for the development of a longitudinal B -field component further from the core in 3C 78 and 3C 264, as well as regions of alternating B -field geometry in 3C 78, as has been observed for a number of BL Lac objects. Taken as a whole, the qualitative and quantitative similarities between the total intensity and polarization structures of 3C 66B, 3C 78, and 3C 264 and those of BL Lac objects are striking, and our images provide at least tentative evidence in support of the standard unification scheme, in which FRIs constitute the parent population of BL Lac objects.

5. We have detected an ordered B -field component on scales as small as ~ 0.3 pc in 3C 66B. Based on the estimated black-hole mass for 3C 66B of $\sim 2 \times 10^9 M_\odot$, we conclude that these B -fields are located within ~ 1650 Schwarzschild radii of the putative central black hole.

6. The modest degree of depolarization inferred for the pc-scale jets of these FRIs is consistent with a dearth of ionized material. This could be due to either the presence of smaller amounts of gas available for ionization, or to a lower flux of ionizing photons. The latter, in turn, could be associated with either a relatively low accretion rate (consistent with the availability of relatively smaller amounts of gas), or alternatively with inefficient radiation of the accretion disk (Reynolds et al. 1996).

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Table 1: Measured and derived parameters for the four FRI radio galaxies

Source Name	S_{VLBI} (mJy)	R_j	P_{peak} (mJy/bm)	P_{rms} (μ Jy/bm)	m_c %	m_{i-j} %	m_{o-j} %	B_{i-j}	B_{o-j}
3C 66B	195	23.4	0.68	56	1.1	0.8	...	\perp	...
3C 78	585	133.8	1.36	104	...	0.6	4.6	\perp	\parallel, \perp
3C 264	206	51.4	1.09	76	0.6	0.7	9.3	Unclear	\parallel
3C 270	429	2.0	0.70	78	0.4

Col. 2: Total VLBI flux density in mJy at 8.4 GHz; Col. 3: Jet-to-counter-jet ratio estimated ~ 1 pc from the core; Col. 4: Peak surface brightness of the P map in mJy/beam; Col. 5: rms noise in the P map in μ Jy/beam; Col.s 6, 7: Fractional polarization in the VLBI core and the inner jet within ~ 0.5 pc of the core, respectively; Col. 8: Fractional polarization in the outer jet $\sim 0.5 - 1.0$ pc from core and Col.s 9,10: Inferred B -field geometry in the inner and outer jet, respectively, relative to the local jet direction, assuming that the jet emission is optically thin (\perp = perpendicular, \parallel = parallel; Unclear = affected by resolution and/or Faraday rotation effects, see section 3).

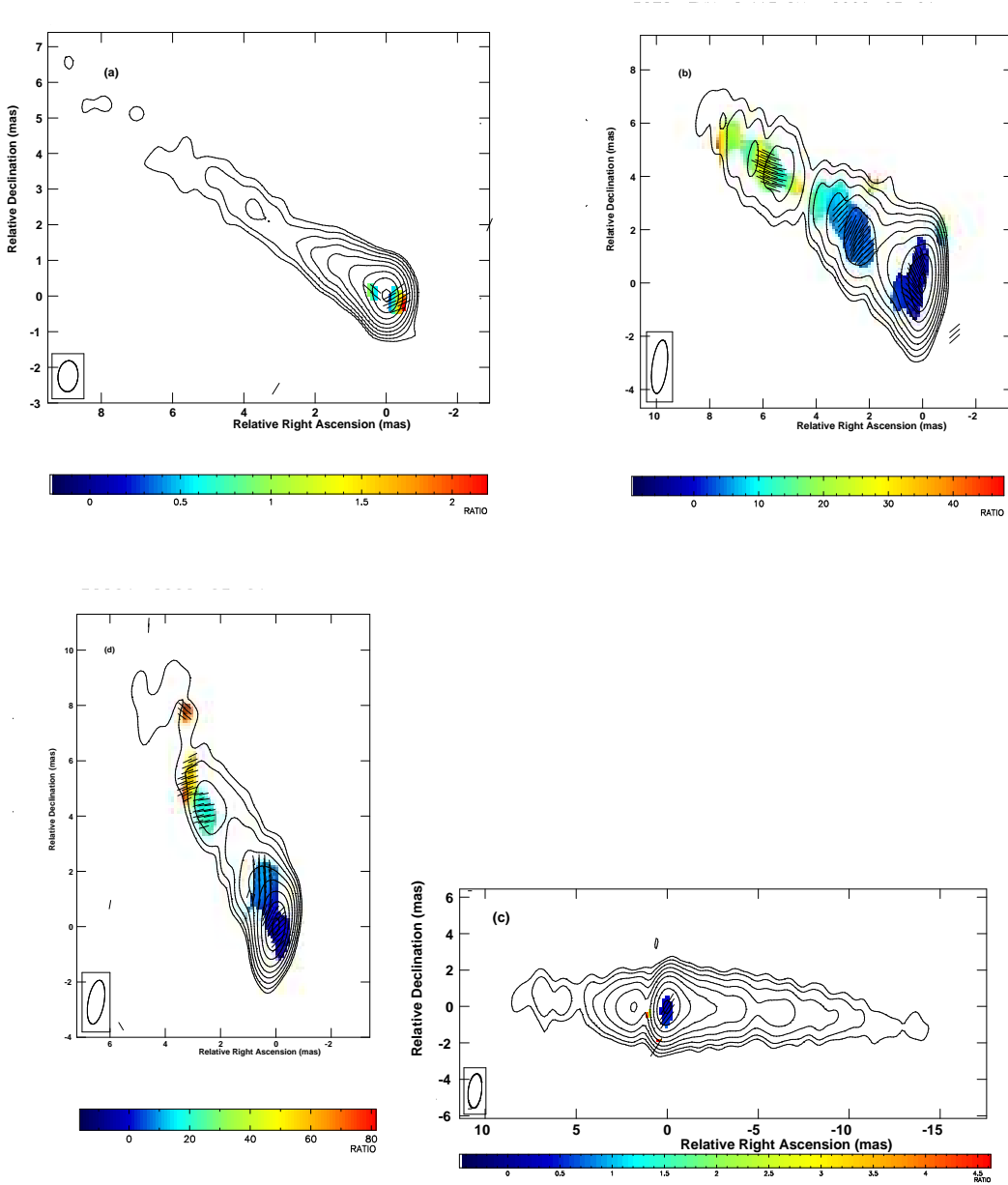


Fig. 1.— Total intensity maps of four FRI radio galaxies with polarization electric vectors and the distribution of the degree of polarization (in %, in color) superimposed. *Clockwise from top left:* 3C 66B, 3C 78, 3C 270 and 3C 264. The surface brightness peaks in mJy/beam are 3C 66B: 118.2, 3C 78: 285.9, 3C 270: 165.3, 3C 264: 136.3. In all cases the lowest contour is $\pm 0.35\%$ of the peak surface brightness, and the contour levels are in percentage of the peak, increasing in steps of two. Both 3C 66B and 3C 78 display predominantly transverse B -fields in their jets, as is the case in BL Lac objects, while the B -field orientation in the jet of 3C 264 is unclear close to the core (*cf.* section 3) and predominantly longitudinal at larger distances along the jet.